

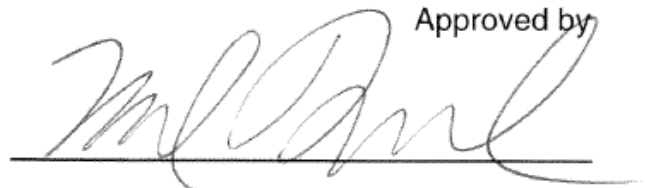
An Exploratory Study of Ephemeral Snow Cover in the Midwest and the Potential Hydrologic Impacts on the Great Lakes with a Warming Climate

Senior Thesis

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Bachelor of Science Degree
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By

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ABSTRACT

Snow cover in the Midwest is a primary contributor to the hydrologic cycle and has significant surface energy balance, biogeochemical, ecological, and societal impacts. This exploratory study addresses some of these issues and looks at some of the primary drivers that affect a snow cover in the Midwest. Much of this region is dominated by an ephemeral snow cover, so the first issue to be addressed is to define what is meant by ephemeral snow and where exactly it transitions into an all-winter (seasonal) snow cover in the Midwest. An ephemeral snow cover is one that comes and goes throughout the winter months, having no seasonal duration. For example in Columbus, Ohio winter average temperature is 2° Celsius, and snow cover has a typical duration of less than 15 days. How well can average winter temperature be used to predict duration of snow cover throughout the winter months? I found that when comparing snow duration to average winter temperatures it is seen that there is an 11 day increase with each degree Celsius decrease. The third and final issue is a look at how the hydrology of the Great Lakes region will be affected by a temperature increase of 2° Celsius. My research shows that as much as 25 percent of the snow cover in the Great Lakes Basins will shift from a seasonal to an ephemeral snow pack with a 2° increase. There is a transition zone at an average winter air temperature of -4° to -6° Celsius where the seasonal pattern shifts from a seasonal snow cover to more of an ephemeral pattern. If we were to experience a 2° increase, the areas on this border of a seasonal snow cover would inevitably shift from a seasonal to ephemeral snow, and would have 15 to 20 days fewer of snow cover a year. These ‘at risk’ areas would have implications on the Great Lakes if they were to begin to provide runoff throughout the winter as opposed to having a single spring melt event yearly.

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INTRODUCTION

The Great Lakes are one of the world's major freshwater resources as they contain approximately $23,000\text{km}^3$ of water and represent about 20% of the world's fresh surface water (Hartmann, 1990). Snow cover in the Midwest is a primary contributor to the hydrologic cycle and has significant surface energy balance, biogeochemical, ecological, and societal impacts in the Great Lakes Basin region. This exploratory study will explore the driving forces behind seasonal and ephemeral snow covers throughout this region and how they will be affected in a warming climate.

The Great Lakes System extends over 3200km from the Western edge of Lake Superior to the Moses-Saunders Power Dam on the St. Lawrence River. In Figure 1 I show the extent of each Lake basin and how they are divided into individual watersheds. Over this distance, the water surface drops in a cascade from 182m to sea level (Hartmann, 1990). Lake levels are determined by the hydrologic cycle in these basins which have major impacts on their surrounding areas. Although efforts are being made to conserve and reuse this water, population is a major concern of the future. Dziegielewski (2008) explained that although water demands can be reduced through conservation and reuse, it is anticipated that 20% to 50% more water will be required in the decades ahead to meet the needs of Illinois' residents and economy. This problem of reduced lake levels and increased population in this area should be of great future concern for management strategies for allocating this water sufficiently.

Lake levels in the Great Lakes basin are determined by the hydrologic cycle and this is why it is important to understand future precipitation scenarios. Although annual fluctuations result in most of the variability leading to record high or low lake levels, seasonal cycles also play a major

role in lake level fluctuations (Hartmann, 1990). During the spring, when snow begins to melt and precipitation increases, lake levels begin to rise until they reach their maximum levels in the summer, then retreat back in the fall. With a warming climate, depending on the basin location, this onset of melt will come earlier in the spring and have lasting impacts year-round on the entire Great Lakes Basin. The possible impacts from declining water levels in the Great Lakes range from environmental (e.g., loss of wetlands, changes in shoreline) to socioeconomic (e.g., loss of hydropower, increased navigation challenge, loss of shipping, reduced marine access) (Hartmann, 1990).

A major challenge we face with understanding the future of precipitation over the Great Lakes is modeling consistency. Future precipitation scenarios over this region due to greenhouse gas-induced climate change scenarios are still very uncertain. Angel and Kunkel (2010) discussed results from Global Climate Models (GCMs) for doubling CO₂ to show both large reductions in the net basin supply (the sum of precipitation over the lakes and runoff into the lakes minus evaporation from the lake surfaces) and slight increases in net basin supply. It is important to acknowledge that even though we know CO₂ emissions will be increasing in the future, we still cannot say with much confidence that this will cause lake levels to decrease.

Another challenge faced when trying to understand snow is how well it can be mapped using satellites and other ground based data. Hall et al. (2010) explained how understanding how well ephemeral snow can be mapped via satellite and the limitations of the different methods are important for mapping the extent of ephemeral snow. According to Dr. Matthew Sturm (Sturm and Holmgren, 1995), whose snow classification scheme is accepted and used worldwide, ephemeral snow is a thin, extremely warm snow cover which often consists of a single snowfall,

which melts away, then a new snow cover reforms at the next snowfall. Sturm also uses a 60 day snowpack as the cutoff between ephemeral and seasonal snow. Sturm's Classification gets much of the Midwest region incorrect, classifying much of it as maritime as opposed to ephemeral (Figure 2). The extent of ephemeral snow is something I attempt to map in this exploratory study based on this description given by Dr. Sturm. In Hall's study, she used North Carolina as a prime example and compared the different satellite-based techniques for measuring both a seasonal snow cover (Appalachian Mountains) and an ephemeral snow cover (Central/Eastern North Carolina). What she determined was that some methods could be accurate when there was no cloud cover but the best overall methods used a combination of satellites and ground station data (Hall et al., 2010). This poses a challenge because we do not have enough snow stations worldwide, nor in the Great Lakes Basin region, to accurately map the extent of ephemeral and seasonal snow.

This study is focused on expanding upon Sturm's classification of ephemeral snow and exploring the relationship between winter air temperatures and snow cover. To understand where a snow cover shifts from seasonal to ephemeral requires understanding the relationships between air temperatures, latitude, total snow cover days, and average snow cover duration. Once the difference between these two snow covers is established, we can map the extent of the two throughout the Great Lakes basin as well as how it will shift with a warming climate.

METHODS

Historical Climate Data Analysis

The groundwork necessary to complete this study came from the analysis of data from the Midwestern Regional Climate Center (MRCC) historical climate database. In total, I compiled data from 107 climate stations in the Midwest United States, focusing mainly around the Great Lakes region. The majority of the climate stations used were from airports because they kept the most complete record of daily data. Snowboards are primarily used at these stations to accurately measure snow accumulation. A snowboard is simply a flat, white board that is placed on the ground and used with a measuring stick to take continuous depth measurements throughout the day. I initially set out with the primary goal to examine the relationships between winter temperatures, snow cover, and latitude. This process began with the tedious job of quality checking the data at each station to see if there were any missing days throughout the history of the station.

After determining winter average air temperatures at each station (months November through March, using average of maximum and minimum daily temperatures) as well as average number of snow cover days, it became very apparent that both were primarily driven by latitude. In Figure 3 you can see the comparison between a winter ephemeral snow pack at a station in Ohio and a seasonal snowpack at a station in Michigan. While they both have an onset of snow cover in November, the Michigan station never melts until sometime in March while the Ohio station comes and goes throughout the winter months. Energy fluxes are determined by the total number of snow days, whereas hydrologic residence time, which governs the release of snow from the land surface to the lakes, is governed by snow duration. Therefore I needed to create a

variable that accounted for the duration for which a snow pack lasted before melting. In creating this new snow duration variable I took the longest string of days in which snow is continuously on the ground for each year of climate data. Then I took the median string over all the years at a given station to define the snow duration for that station. This new median snow duration parameter is a much more proficient way deciding whether a station is, on average, an ephemeral or a seasonal snow pack.

Contour Mapping and Correlation

The next part of my analysis was to create contour maps over this region with the data from the climate stations. The first set of contours I created was for average winter air temperatures. As expected, you can see in Figure 4 that these contours correlate very well with latitude, with a few outliers due to higher elevations in the Appalachian Mountain Range. The next set of contours was for median snow duration, which I overlaid atop the winter temperature contours. Once again there was a strong correlation with duration and latitude, increasing as you travel further North.

The most important observation to come from this map was that the -4 degree Celsius average winter temperature contour was very closely intertwined with the 60 day duration contour. In later analysis I show that the -4 degrees Celsius line marks the transition of days and duration closing together. Now we see that -4 degrees Celsius is strongly correlated with a median winter duration of 60 days, or two months of continuous snow pack. From these two observations I decided to use this line as my transition between an ephemeral and seasonal snow pack for the upcoming analysis.

Basin Area Analysis

The final part of my study takes a look at how the snow cover regime of the Great Lakes will change if Global temperatures were to increase by two degrees Celsius. I began by calculating the area of the watersheds within each Lake Basin boundary. Then I split those areas into ephemeral and seasonal using the transition line of the -4 degree Celsius contour. In Figure 4 this would be red showing all of the ephemeral watersheds and both blue and green showing the seasonal watersheds.

Next I found the area of the watersheds between the -4 and -6 degree Celsius contours because with a 2 degree increase the -6 degree contour would become -4 degrees. These 'at risk' watersheds are colored green in Figure 4 and represent the total area in the region that would shift from seasonal to ephemeral snow with this temperature increase.

Then I broke these watershed areas into each individual basin and calculated the percentage of each basin that would change from seasonal to ephemeral (Figures 5 and 6). The same data is displayed a little differently in Figure 7 but combined into a single graph showing what is currently seasonal, ephemeral, and what is at risk. Calculating the percent area change over the Great Lakes Basin concluded the analysis of my study.

RESULTS

Discovering the fundamental relationship between average winter snow temperatures and snow duration was the most important results for understanding what drives a seasonal snow pack. As expected, there was a strong correlation between latitude and average winter air temperature.

There is also a fairly strong relationship between both the number of snow days and snow duration, and average winter air temperatures (Figure 8). With some analysis of this plot we see that there is a slope of -11 between -2 and -8 degrees Celsius for snow duration, meaning that with each Degree increase you lose 11 days of snow duration. Throughout the 107 climate stations used there is a minimum of a one day duration in Chattanooga, Tennessee and a maximum duration of 114 days in Hancock, Michigan.

Looking further at Figure 8, we see that between 0 and 8 degrees Celsius there are very few snow days, but between -2 to 0 degrees Celsius there grows a disconnect between total days and duration. In Figure 9 this disconnect is apparent at the ephemeral Ohio station while the days and duration are very similar at the seasonal Michigan station. Once the average temperatures reach -4 degrees Celsius and colder though that gap begins to close, representing more of a seasonal pack as the days and duration are more similar.

By determining that the transition occurs at the -4 degree Celsius contour where we also have an average duration of 60 days, I could then show how that line would shift with a warming climate. The area change analysis showed that there would be a total percent area change of 28 percent with just a 2 degree Celsius increase. Lake Erie and Ontario would remain completely ephemeral while Lake Superior would remain seasonal. But Lake Michigan and Huron, as well as the St. Lawrence Seaway would experience significant watershed shifts, with the St. Lawrence Seaway experiencing an astounding 73 percent change.

DISCUSSION

Based on this preliminary study, I hypothesize that with a two degree Celsius increase about one-fourth of the Great Lakes Basins would shift from a seasonal to ephemeral snowpack, so what are the implications? These two snow packs behave very differently throughout the winter months and the effects they have on the Lake System as a whole are quite vast. The most obvious difference is that as you shift from seasonal to ephemeral, spring melt, which is a major contributor to the Great Lakes, would no longer provide a single massive runoff pulse at the beginning of spring. It would instead provide a small amount of runoff consistently throughout the winter months and this can have both environmental and socioeconomic effects.

This large shift would also suggest that there would be a major increase in snow-free days which has an effect on albedo and solar radiation at the surface. This type of negative feedback of albedo can result in changes in land-atmosphere interactions which could potentially affect synoptic scale weather systems. These weather systems are forced by local convective processes, so disturbing the energy flux would inevitably lead to change. It is still uncertain whether this type of warming will lead to more or less precipitation over the Great Lakes Region, but change will occur and we need to plan accordingly.

SUGGESTIONS FOR FUTURE WORK

Due to the fact that this was an exploratory study there is plenty of opportunity to expand upon this research. One thing I would like to incorporate into the study would be stream gauge data. This would be very beneficial for better understanding the timing of a single, large runoff pulse event versus small, year around pulses that would occur in an ephemeral snow region. I would

also like to do analysis on Canadian historical climate stations as my MRCC database only had data for the United States. It would not be possible to make serious conclusions about the hydrology of the Great Lakes without incorporating Canadian station data into the study.

The second area I would like to incorporate into this work would be a geochemical approach to better understand the affects of nutrient rich snow melt on the Great Lakes region. Lakes such as Erie are already experiencing Harmful Algae Blooms (HABs) because with a runoff coming year round into the Lake, it never has a chance to freeze over and kill off the existing algae. What are the main geochemical contributors that facilitate these algae blooms and how much of it is anthropogenically induced?

Another interesting direction would be to use the relationships between snow durations and temperatures to map snow elsewhere throughout the world. My main motivation from the beginning to determine the difference between an ephemeral and a seasonal snow pack was to better refine Matthew Sturm's Snow Class distribution map (Figure 1). It was difficult in the literature review to find any solid parameters for classifying an ephemeral snow pack, so therefore I needed to understand what defined it before it could be mapped. Contributing in any way to the mapping of snow class distribution around the world would be very rewarding.

Figures

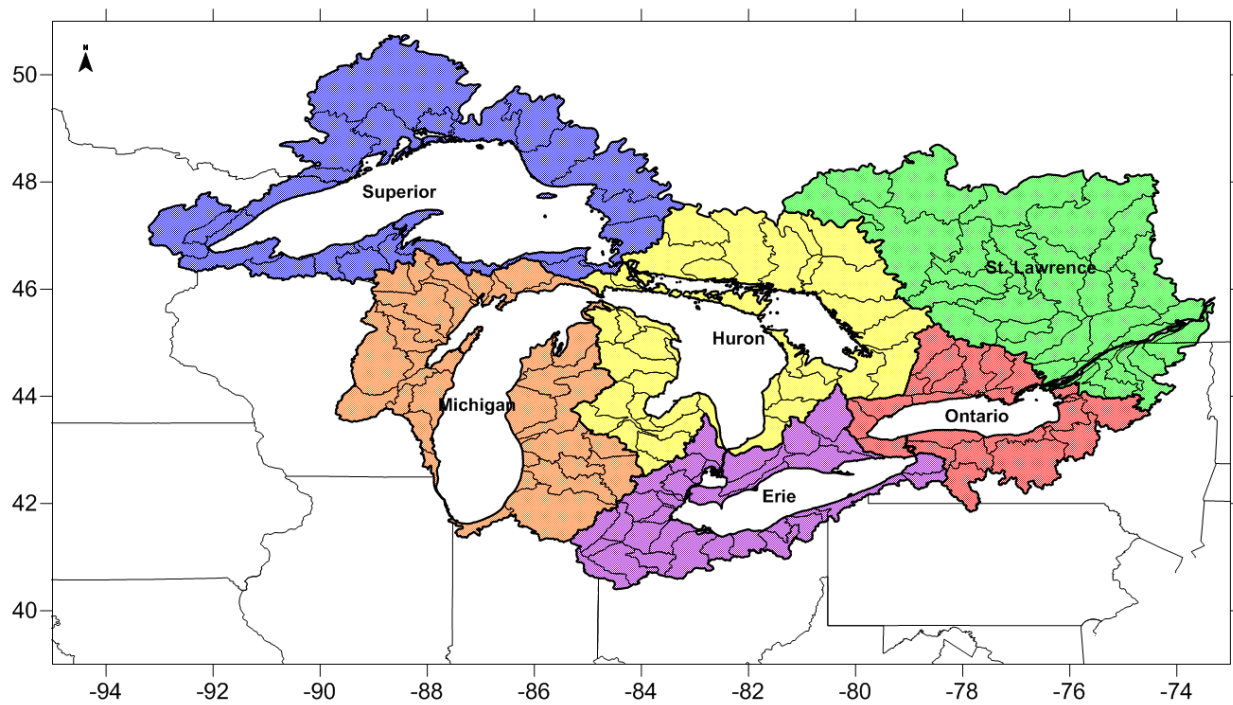


Figure 1. A map of the Great Lakes Basin System. Each Lake basin is represented by a different color with the individual watershed boundaries displayed within.

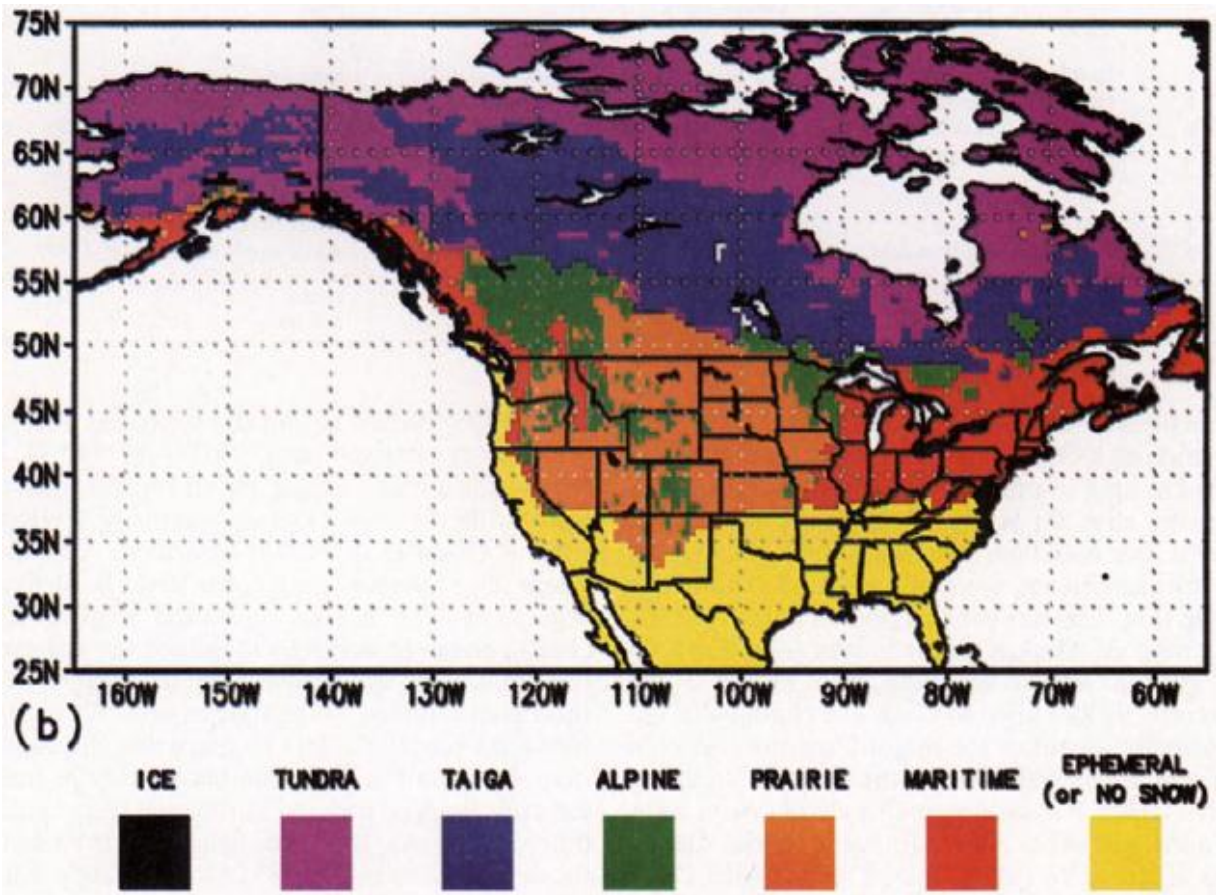


Figure 2. Matthew Sturm's snow class distribution based on climate variables in North America (Sturm and Holmgren, 1995).

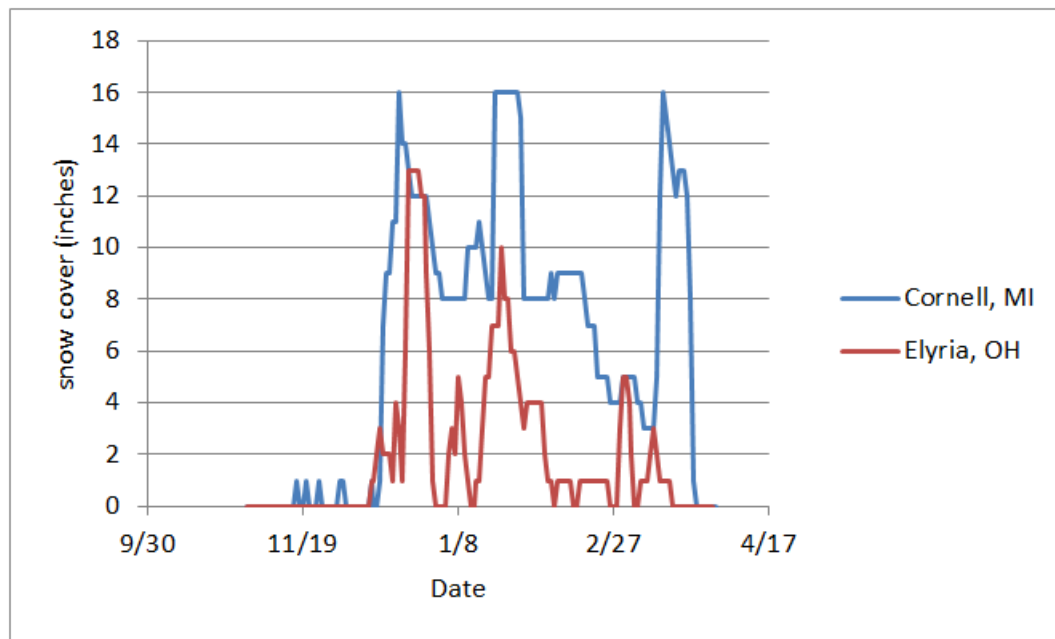


Figure 3. Scatterplot displaying a time-lapse of a typical winter snow cover for both an ephemeral (Elyria, OH) and seasonal (Cornell, MI) snowpack.

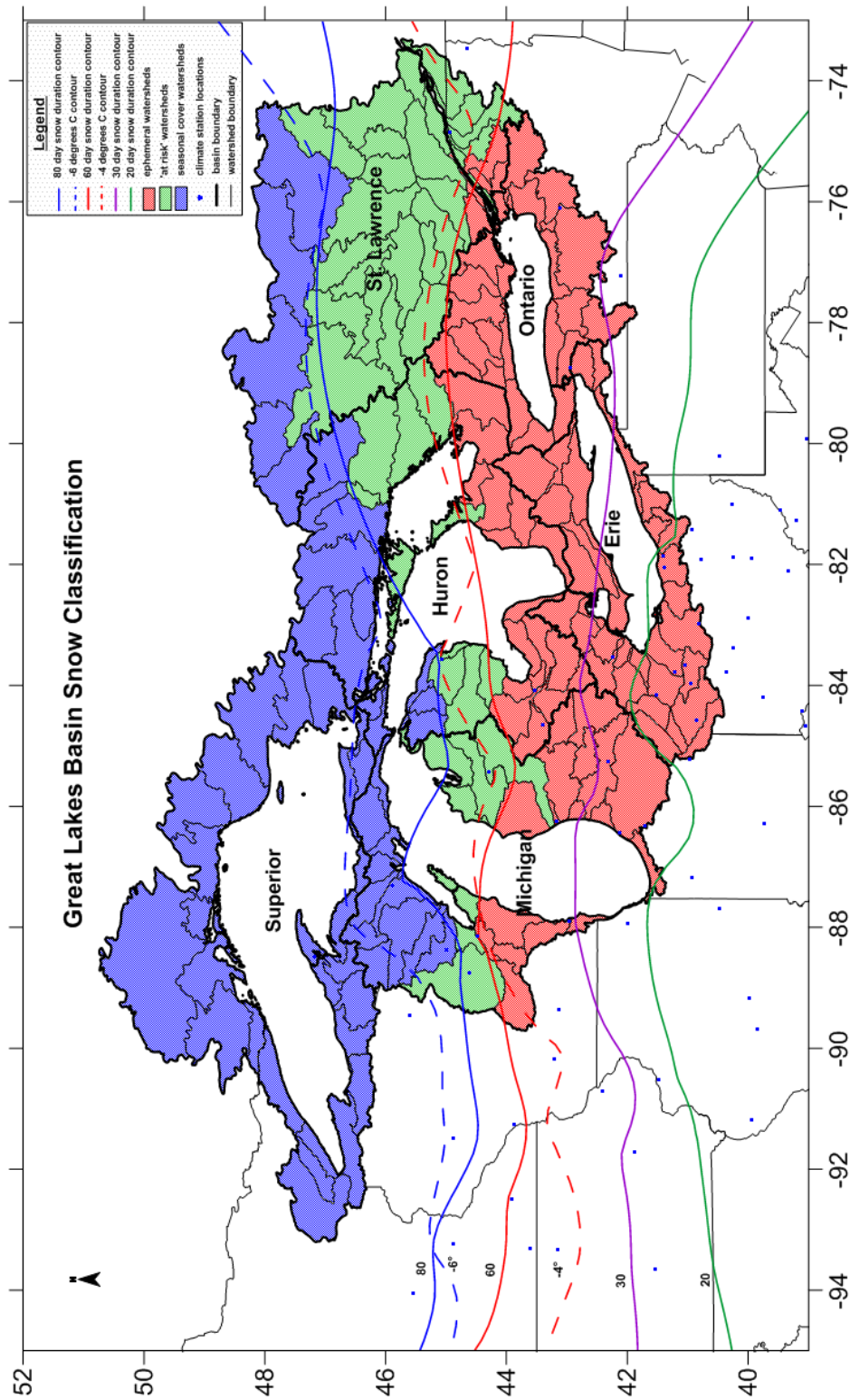


Figure 4. Great Lakes Basin snow classification map.

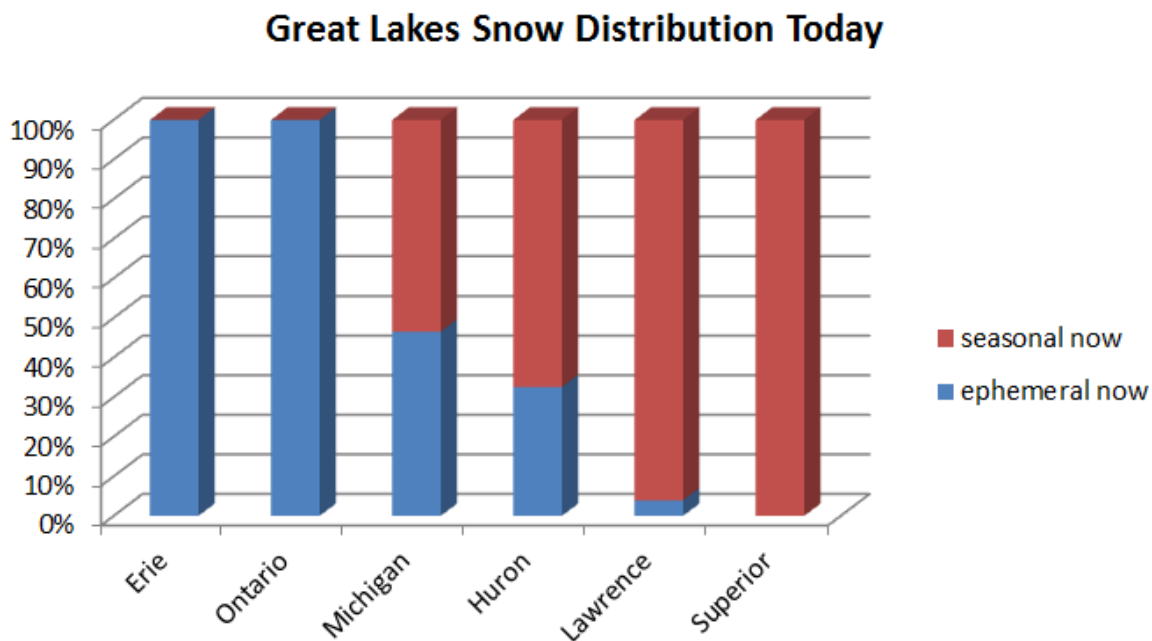


Figure 5. Great Lakes Basin snow class distribution in 2012.

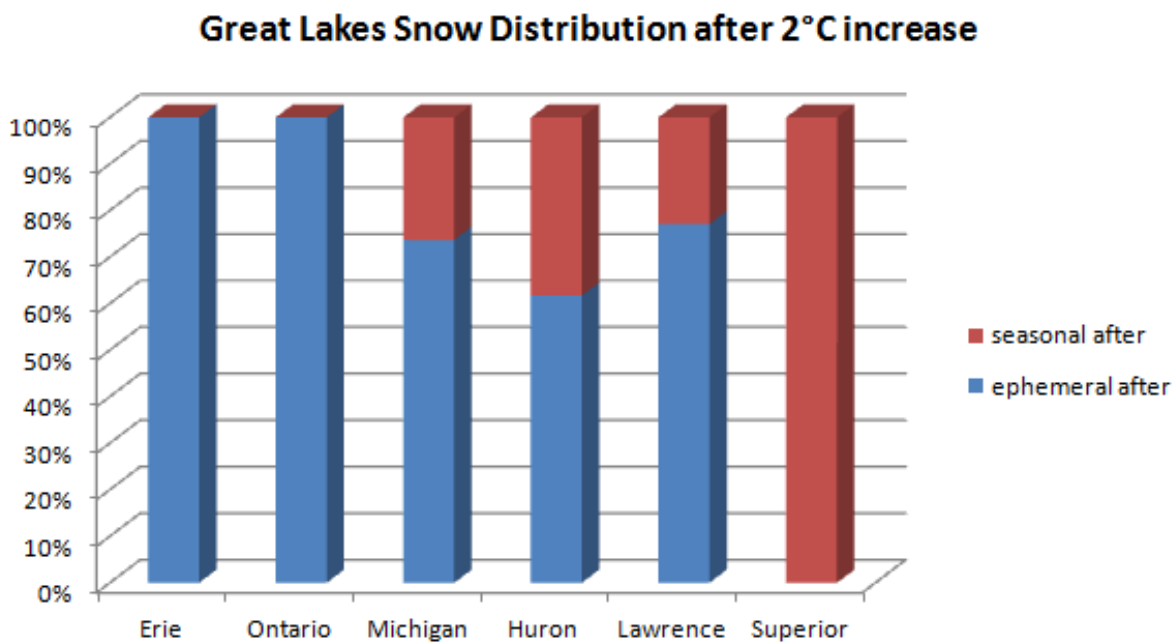


Figure 6. Great Lakes Basin snow class distribution after 2° Celsius increase.

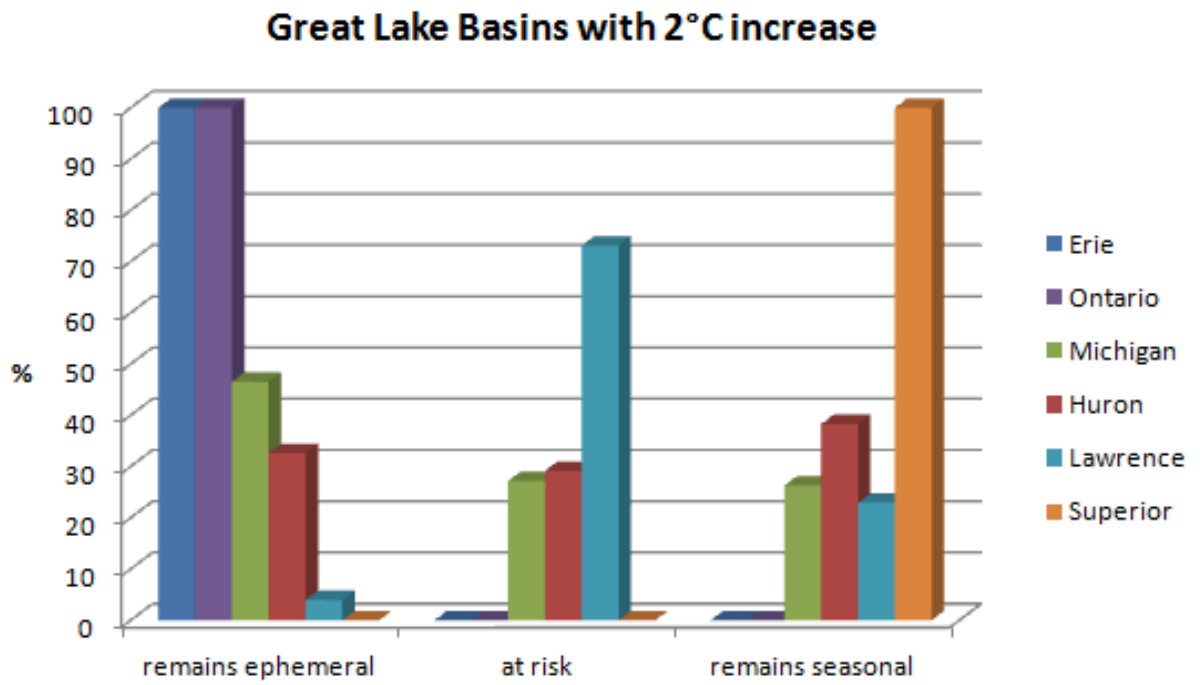


Figure 7. Great Lakes Basin snow class distribution after 2° Celsius increase.

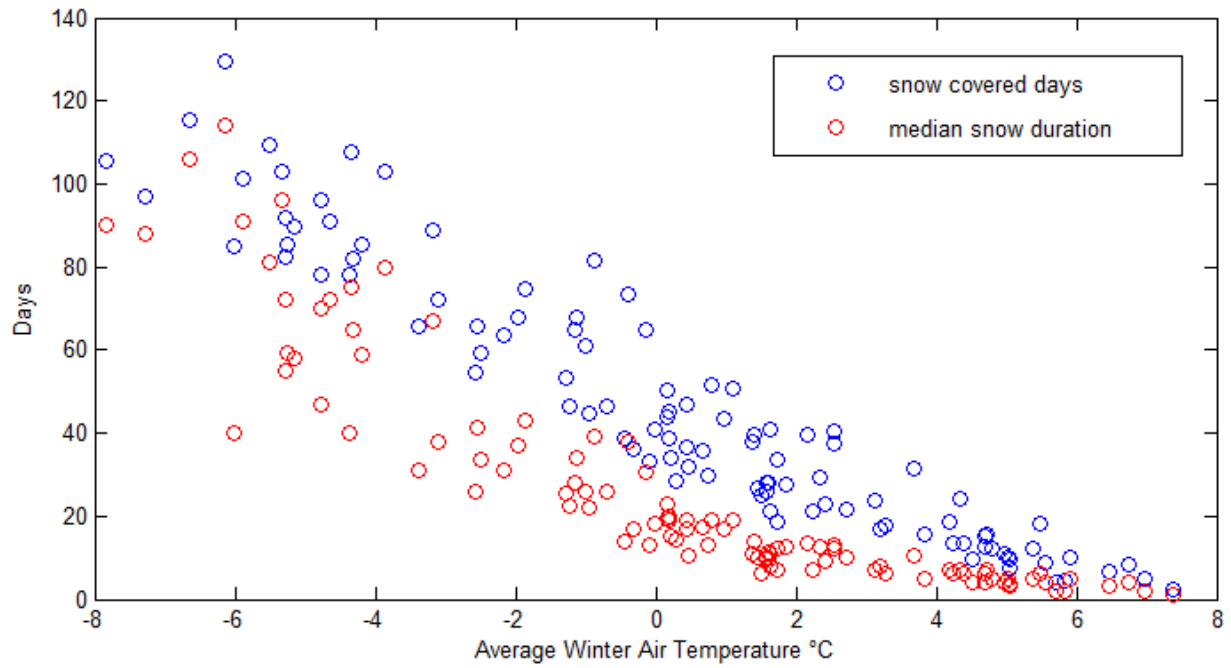


Figure 8. Plot showing the relationship between average winter air temperatures versus total snow covered days and average snow duration.

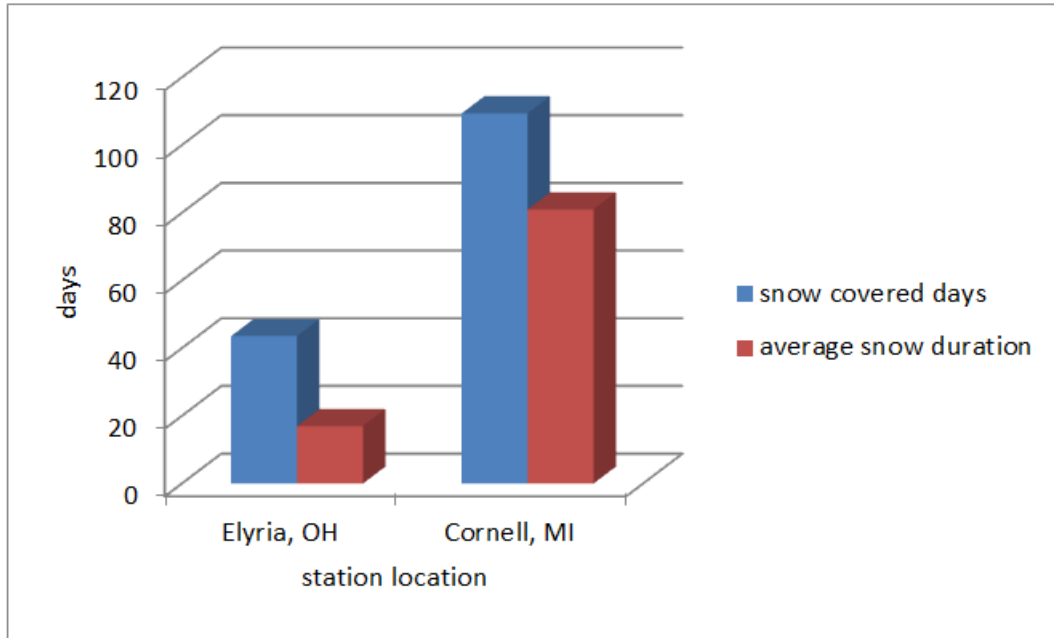


Figure 9. Graph comparing snow covered days to average snow duration at representative ephemeral and seasonal stations.

References Cited

- Angel, James, and Kenneth Kunkel. "The Response of Great Lakes Water Levels to Future Climate Scenarios with an Emphasis on Lake Michigan-Huron." *Journal of Great Lakes Research*.36 (2009): 51-8.
- Dziegielewski, B. "Regional water demand scenarios for northeastern Illinois: 2005-2050." Project Completion Report prepared for Chicago Metropolitan Agency for Planning (CMAP) (2008).
- Hall, Dorothy, et al. "A Comparison of Satellite-Derived Snow Maps with a Focus on Ephemeral Snow in North Carolina." *67th Eastern Snow Conference* (2010), http://www.appstate.edu/~perrylb/Research/Publications/Proceedings/HALL_etal_ESC2010.pdf
- Hartmann, Holly. "Climate Change Impacts on Laurentian Great Lakes Levels." *Climate Change*.17 (1990): 49-67.
- Sturm, Matthew, and Jon Holmgren. "A Seasonal Snow Cover Classification System for Local to Global Applications." *American Meteorological Society* 8 (1995): 1261-83.